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An Integrated Mathematical Approach to Measure the Capacity of MMTS

Bayan Bevrani, Robert L. Burdett, Prasad KDV. Yarlagadda

Abstract**—**This article focusses upon multi-modal transportation systems (MMTS) and the issues surrounding the determination of system capacity. For that purpose a multi-objective framework is advocated that integrates all the different modes and many different competing capacity objectives. This framework is analytical in nature and facilitates a variety of capacity querying and capacity expansion planning.

Keywords**—**Analytical model, capacity analysis, capacity query, multi-modal transportation system.

I. Introduction

A. Background

MULTI modal transportation systems (MMTS) occur in most developed cities and towns. MMTS are complex systems and consist of many different transportation modes, locations, corridors, and services. Without loss of generality the purpose of MMTS and their component parts is to efficiently transport passengers, vehicles and freight between many different locations. It should be noted that the development of MMTS has a great effect on the economic health of a region. According to Meyer and Miller [11] "the economic health of a region depends of the flow of goods and people and information within and around a metropolitan area". It is evident that the different modes within a MMTS should be highly connected, synchronized and complementary to each other in terms of capacity and function. Unfortunately, this is rarely true, due in part to the ad-hoc and independently considered expansion of the individual parts over time and the changing nature of demand over time. In addition when planning activities are considered jointly, it is performed in an incomplete and limited way. Federal governments in many countries are actively proceeding with the expenditure of billions of dollars on intercity and regional passenger rail and road projects. Travel demand in urban transportation networks is continuously increasing and this is a challenging and important issue for decision makers. There is a lack of accepted tools for documenting the interrelationship between these public modal investments. In many parts of the world, rail and road investments are seen as complementary elements of a larger multimodal and intermodal public policy. Approval of new runway capacity and planning for connecting rail services are seen as part of one larger public policy debate.

The different transportation modes have been created for many different clienteles, many of which compete with each other, within a particular transportation mode or else across the entire MMTS. The capacity of road and especially the capacity of freeways is an essential input of the planning, design, and operation of roads. The capacity can assist planners to predict the times and locations where congestion and delay will occur and the traffic to be expected in bottlenecks. Hence, it is important that capacity can be defined, measured, and used in modelling and decision making [12]. In today world road networks are highly congested and the existing road networks cannot be expanded easily and economically. Hence, roads and other forms of transportations need to be developed and expanded in order to facilitate increasing demand.

B. Research Aims

This article considers how to improve multi-model transportation systems. There are many different modes in MMTS. They include bicycle, rail, bus, pedestrian, and roads. In this article, a subset of these, namely road, rail, and bus are considered. This is because the demands upon them are significantly higher and they constitute the most important part of MMTS. The expansion of these transportation modes is a difficult, complex and politically sensitive topic. Consequently that topic is addressed in this article. The primary aim of this research is to identify methods that can be used to identify and expand MMTS capacity. Opportunities for the development of capacity expansion planning models for railways and roads are considered. The development of a holistic framework for analysing the capacity of MMTS is necessary. In our opinion a framework such as this is necessary is to answer questions related to the capacity of MMTS. The issues and complexities involved in this task are investigated. A preliminary capacity querying framework for MMTS is proposed. Capacity models and expansion variants are advocated as the foundation of that approach. As capacity models of the aforementioned type are not beneficial in isolation we advocate that they are embedded within a decision support tool. This article does not focus upon how commuters use the MMTS network per se.

In this article, the possibility of developing a multi-objective model for MMTS has also been investigated. As the needs of different clientele are in conflict, multi-objective theory seems to be necessary to balance and regulate the different competitions. To our knowledge, there is little research on multi-objective optimization models for capacity determination of MMTS.

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C. Literature Review

This section reviews the state of research on MMTS planning and decision making. An investigation of the literature indicates that planning is an important way of increasing the efficiency of MMTS. In the past, however transportation planning has often exclusively focused upon highway network expansion [11].

Previous research on MMTS research has focused upon creating an efficient transportation network. This can indirectly increase the capacity of MMTS. There is a need for techniques that evaluate the capacity of the whole transportation system that considers all feasible modes [1], [10], [15]. For instance Park [15] presented an advanced method that can serve as an analytical tool for strategic planning of multimodal transportation system for both freight and commuters. He introduced a bi-level problem that considered many crucial factors including multiple modes and commodities, behavioural aspects of network users, external factors as well as the physical and operational conditions of a network. The model could estimate the capacity of a multimodal network, and also identify the existing capacity gaps over all individual facilities in the network. This capacity model can help practitioners and planners to achieve their aim of developing sustainable transportation system in a cost-effective manner.

Some types of MMTS can carry thousands of containers and commuters on trains and roads. To ensure that trucks return home within a specified time, and empty containers are accessible at the scheduled time, in the right place, careful planning is required. Jansen, Swinkels et al. [9] studied these repositioning aspects of MMTS in order to get a cost-efficient solution. They introduced a plan for MMTS system which is both flexible for adaptable. It is described as useful for daily planning and also supports the operations of a MMTS. Yang et al. [17] developed a model for road network capacity. They proposed a bi-level optimization model to efficiently determine the maximum number of trip from each origin. Their model can assist in identifying whether an existing transport network is capable of supporting future urban growth.

Prior research has studied the effect of toll cost on the capacity of transportation network. For example, Xiao et al [16] studied the competition and efficiency of private toll roads. Their paper focused on toll and capacity competition among private roads with congestion in a network with parallel links. Their study considered both pricing and capacity choices in order to achieve equilibrium within the network. They reported that more competition does not necessarily lead to less congestion on the roads. They also claimed that the tolls and capacities converge to the socially optimal level if the state of limited competition for market of different number of roads turns to perfect competition.

Prior research on multimodal transportation system has also considered the problem of finding shortest paths between specific origin-destinations in urban systems. For instance Modesti and Sciomachen [14] introduced an intermodal path planning model that minimizes the overall cost, time and users discommodity associated with the required paths. The shortest path study was continued by Choi, Cho et al. [7] to find out a feasible area with an effective time range and effective cost range in order to get multiple Pareto optimal solutions. They also tested the efficiency of the heuristic algorithm for constrained shortest path problem. They found that it can be useful for third party logistics. Later, Zografos and Androutsopoulos [18] presented a new formulation and an algorithm for solving the itinerary planning problem to determine an optimized set of criteria for the itinerary (i.e. total travel time, number of transfers, and total walking and waiting time while departing from the origin and arriving at the destination within specified time). Their model provided fast and accurate solution for the real-life itinerary planning problem.

The models developed in Burdett and Kozan [5] and Kozan and Burdett [8] are essential techniques for the determination of the theoretical capacity of a railway. However they assume a specific proportional mix of trains is defined. Hence as only a single value of capacity is identified, those capacity models can only be used to identify how the infrastructure can be used and whether it can support an intended future traffic load. A more generic multi-objective approach has recently been devised in Burdett [6]. This article is highly relevant to the determination of capacity in MMTS.

II. MMTS Querying

This section discusses the type of questions that need to be answered in relation to the operation and expansion of MMTS. Without loss of generality, we would like to know whether a MMTS can support the flow of enough people, goods and vehicles; and is it doing and accomplishing what it was designed to do. The questions below are address the overriding general questions above and arises in regard to the usage of MMTS. There are three types of questions that are mentioned below:

Question 1 : "How much capacity exists?"

a) How many people can be moved from origin o to destination d in time *T*? (i.e. across all modes)
b) How many people can be moved from origin o to destination d in time *T* with mode m?
c) How many people can be moved between all origins o and destinations d in time *T* with mode m?

Corollary 1 : These questions are particularly useful for determining the effect of special situations like the following: i) lane closures, ii) track closures (i.e. maintenance, failures, terrorist attacks, etc), iii) special event (i.e. sporting, local celebration) where the demand has increased temporarily in certain parts of network.

Question 2 : "Can I meet a given demand?"

a) Can I move x vehicle/passengers from origin o to destination d in time *T*? (i.e. across all modes)
b) Can I move x vehicle/passengers from origin o to destination d in time *T* with mode m?
c) Can I move x vehicle/passengers between all origins o and destinations d in time T with mode M?

Corollary 2 : These questions are particularly useful for identifying whether MMTS can meet intended demands. For example they can help to identify bottlenecks and where expansion activities should be focussed, and where different modes and paths need to be added or developed.

Question 3 : "What time is required?"

a) What time is required to move x vehicle/passengers from origin o to destination d in time across all modes when a distribution of the demand to each mode exists?

b) What time is required to move x vehicle/passengers from origin o to destination d in time with mode m?

Corollary 3 : These questions are useful for predicting the transit time of passengers and vehicles. This information helps people to select a given mode to travel by. These questions help to identify the systems recoverability, for example in the event of a system breakdown. These questions help to identify the performance of the system, and describe how the system copes, or does not cope with specific demands.

General Corollary

All of these questions can be used to query the MMTS for different intervals of time and demands within each day. They can be used in planning, timetabling and rostering. The answer to these questions will allow us to predict future events. We are testing whether the current transportation system or a future system can handle the traffic demand of the future. This information can be used to ensure that current transportation system can be modified in an optimal and cost effective way. These types of questions can help town planners and other government decision makers to analyse the effect of development of a new suburb or the creation of new transport corridors. The effect of changing of components and characteristic and features of current transportation systems can be analysed. For example, add lanes, and section lanes, or add a signal, add new intersections, and add siding to current track. Question 3 can be used for real time traffic control, in the event of accidents, breakdowns, signal failures, track failures, and maintenance. For example, the real time traffic situation can be notified to the passengers.

III. MMTS Capacity

The performance of every system is limited and this is called the capacity of system. Capacity can be defined in various ways. In this article the main focus is the determination of theoretical MMTS capacity. The value of determining theoretical capacity is twofold. First it is a very useful reference point. Second it can be used in high level planning and decision making processes. To obtain the theoretical capacity, a number of simplifying assumptions are often made, and some levels of realism are not incorporated.

The considered MMTS involves roads and rail. The definition of road and rail capacity however differs in the literature. For example in Burdett and Kozan [5], Bevrani et al. [2], [3] and Bevrani [4] the theoretical capacity of a railway corridor is defined as the maximum number of trains that can traverse this corridor in a specified period of time. This definition is extended to that of an entire network. The capacity of a road, according to Minderhoud et al. [12], is the maximum traffic volume that can be achieved over a given time period. In [11] road capacity is similarly defined as the maximum hourly rate at which persons or vehicles can traverse a point or uniform section of a lane or roadway in a given time period.

Without loss of generality the capacity of MMTS is dependent on the capacity of individual modes, and how those modes interact and influence each other. The main difficulty of quantifying the capacity of MMTS is that there are many units of measure. MMTS performance is in terms of vehicles, passengers, and freight movements. Clearly these objects are different and are not always directly comparable or integrated. For instance it is not possible in this context to define capacity as a single value if there is not a "common measure" or unit of capacity (UOC). This difficulty has provided significant motivation for our research and for a multi-objective capacity model (MOCM).

A. A Multi Objective Approach

In this section, the importance and necessity of developing a multi-objective approach for MMTS is discussed. MMTS consist of different modes that can move different numbers of passenger, vehicles and goods. The unit of measurement for capacity could be the number of vehicles, number of passengers, or total weight (i.e. tonnage) of goods.

In a system that includes all of these, the question arises "what is the whole system's capacity?". As the individual units of measure are different, and not directly comparable, a simple answer to this question is difficult. Preliminarily there are two different options that may be feasible. The first option is to define capacity purely as the number of passengers. The number of vehicles could be converted to a number of passengers based upon some distribution of passengers to vehicles.

The second option is to calculate the capacity of MMTS as a tuple, that includes the number of vehicles and the number of passengers, i.e. (#Veh, #Pass). The second option is more preferable for a number of reasons however the main one is that no conversion is needed. A comparison operator however is needed to judge the quality of one capacity solution over another. In laymans terms, there is a need to compare and weight the different numbers of vehicles and passengers in a solution. This is the topic of multi-objective optimization. The algorithms in [13] can be used to sort and partition a set of multi-objective solutions into non-dominated and dominated parts.

The solution of a multi-objective analytical model is a set of non-dominated solutions, aka a Pareto frontier. These solutions are optimal in the sense that there are no other solutions which are strictly better in terms of all of the all objectives. Different preferences can be facilitated and analysed easily once these Pareto optimal solutions have been identified and recorded. The preference information is highly subjective and differs from countries, policies and economic situations. Hence, the preference information structure is required as an input to such an approach.

The number of objectives is potentially large for MMTS. Upon reflection this means that the development of advanced solution techniques may be necessary. Past research rarely has more than two or three objectives. Burdett [6] however has demonstrated that models with many objectives are solvable. They also demonstrated the application of an appropriate solution technique for large multi-objective problems.

B. A Capacity Querying Framework

Capacity querying framework focusses upon answering questions related to the capacity of railway networks via capacity querying methods. Theoretical capacity models can be used as the foundation of this approach. In isolation the aforementioned capacity models are not beneficial, unless they are embedded in a decision support tool. The exact details of the framework are summarized in Fig. 1, i.e. it illustrates capacity querying elements and the interdependencies between them. The link between static capacity querying (CQ) and capacity expansion querying (CEQ) is also shown.

In capacity query CQ1 and CQ2 the target demand is given. The question is whether the network can handle this demand or not. If it can handle the demand the process is finished, otherwise, other possibilities are recommended (i.e. CQ3, and CEQ). CQ4 determines the minimum time for a given mix of trains to traverse the network. CQ3 is only applied when the target demand cannot be met in CQ1 and CQ2. The purpose of the CEQ is to determine how to optimally expand the capacity to meet given target demands and subject to a given budget. The following sub-sections explain each capacity querying in more details.

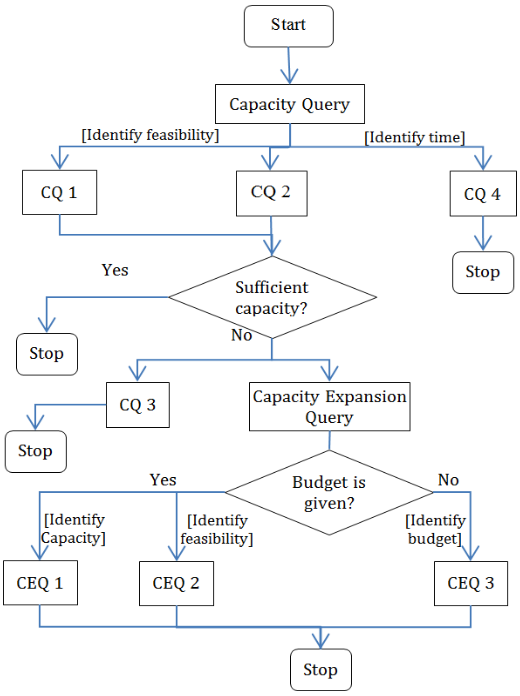

Fig. 1 Flow chart of the capacity querying framework

IV. MMTS Details

There are many different types of MMTS. The three most typical systems are bulk material flow between mine and ports, urban transportation of passengers between different locations, and containerization movements between ports and urban locations. In the first scenario, the modes are rail and road. In the second, all modes occur. In the third, road, rail, sea modes are present. In this article, the main focus is on urban transportation network involving road, rail, and bus ways. It should be noted that the unit of capacity measurement can change within and between based on each MMTS. For example, in mine the tonnage of goods, the total number of passengers in urban transportation, and the number of containers for containerization.

A. Data Requirements

MMTS are large complex systems. To analyse MMTS a large amount of data and information is potentially required. Fortunately much of this information can be obtained from websites and freely accessible documents. All locations, existing paths, length of each path, and available modes for each path should be identified and extracted. However, the accessibility of data concerning the demand of individual modes on individual corridors is more difficult.

B. MMTS Representation

MMTS can be shown and modelled in a variety of different ways. Some variations are explained here. It is generally necessary to model MMTS using networks and network diagrams. Without loss of generality a transportation network is a collection of nodes connected by arcs. Nodes demonstrate origins and destinations (i.e. places where travel begins and ends), and arcs define existing links between nodes. In Fig. 2. some examples are shown.

Here different arcs signify different modes. Directed arcs imply the direction of travel, and undirected arcs imply travel in both directions. Fig. 2a is typical of many urban road networks. It includes both road and pedestrian linkages. Fig. 2b is similar because it also includes pedestrian links. However road and rail paths are also present. This network could demonstrate two adjacent corridors that start and end in the same vicinity like a suburb. Or it could demonstrate two corridors in completely different geographical areas, like in Fig. 2c. Currently in Fig. 2b, there is no direct information to identify which situation is actually occurring. Hence some other information must be included in the network. However, there is a pedestrian link. The existence of a pedestrian link could be used in theory to imply that two locations are close by, i.e. in the same vicinity.

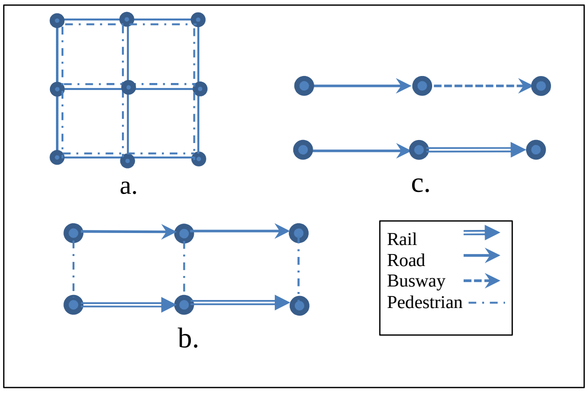

Fig. 2 MMTS networks

V. Conclusion

This article has considered the development of an integrated approach to measure the capacity of a multi-model transportation system. A further requirement to expand such systems has also been considered. The innovation of our proposed analysis and solution methodology is that it integrates all modes. Past research on transportation networks has primarily considered roads, however railway networks are seldom investigated and are not integrated with road based approaches.

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